Final report

Magmatism-induced carbon escape from marine sediments as a climate driver - Guaymas Basin, Gulf of California (MAKS)

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1. Brief Summary

1.1. Scope

During the geological past there were episodes of significant carbon injection from the geosphere into the atmosphere. One example is the Paleocene Eocene Thermal Maximum (PETM) – a time when an injection of approximately 2000 Gt of carbon into the atmosphere warmed global climate by up to 8 degree C on a global average. Modeling suggests that this carbon injection must have been quite short-lived, i.e. a few tens of thousands of years, in order to create the atmospheric signal. To improve future climate models it is tantamount to decipher which geological processes have caused the large-scale carbon injection, and whether such processes may be triggered by human action. Unfortunately, this is not clear so far. The two most likely hypotheses for the PETM are gas hydrate dissociation and carbon release due to contact metamorphosis around igneous intrusions into marine sediments predominantly when large igneous provinces get emplaced during continental break-up. We have tested this second hypothesis by conducting a research expedition on RV Sonne during a 31-day cruise to the Guaymas Basin in the Gulf of California which is the only known place in the world in which magmatic intrusions presently intrude into organic rich marine sediments. We have mapped the magmatic intrusions in three dimensions to determine their thickness and extent and to determine how carbon is transported to the seabed. In addition we have carried out a geochemical sampling programme in order to determine how much carbon is released over time. Carbon is released only for a short time after the intrusions, but then very vigorously. Therefore, the Guaymas Basin is a good analogue for the North Atlantic Volcanic Province during the Paleocene Eocene Thermal Maximum when carbon injection was short-lived and vigorous. In particular our finding that methane and CO_2 are injected very fast and high up into the water column means that sill intrusions are a powerful driver in climate change. The bottom line is that after having conducted this project it is much more likely that the PETM was caused by volcanic intrusions into the sedimentary basins around the North Atlantic than by hydrate dissociation or other geological drivers.

1.2. Circumstances under which the project was conducted

The project was proposed to the BMBF funding line for conducting strategic research into Earth System processes under the FONA Program. As such it was

completely detached from the Helmholtz funding stream through Program-oriented funding (POF) OCEANS under which GEOMAR is conducting research into resources and geohazards.

1.3. Planning and schedule

The project was proposed for the first time in September 2011. It was accepted in 2014 and the project was running from 1.3.2015 to 31.8.2017. The cruise took place from 23.6.2015 to 24.7.2015. While the first 3 months before the cruise were dedicated to equipment preparation and logistics, the time between the cruise and the termination of the project was spent on data evaluation.

1.4. Scientific and technical baseline

There were several episodes in Earth's history when climate changed because of large-scale injection of carbon into the atmosphere. The most carefully investigated example of such a climate event is the Paleocene-Eocene Thermal maximum (PETM) during which Earth's atmosphere warmed by about 8 °C over a time span of less than 10,000 years (Zachos et al., 2003). This change has been confirmed by ODP and IODP wells. Climate models based on carbon isotope records and other data suggest that the PETM was initiated by an input of about 2000 Gigatonnes (Gt) of carbon into the atmosphere (Dickens, 2003; Zachos et al., 2008). In comparison, today's atmosphere contains about 800 Gt of carbon (IPCC, 2007). Injection of such a large volume of carbon cannot be explained by the general dynamics of the Earth and ocean systems, for which material cycles and interactions are well known, but requires an external geological source. Finding this source and understanding its dynamics are of major importance for climate sciences. For example, if the source can be triggered by anthropogenic factors, it is vital to include it in climate models and possibly even Climate Engineering measures.

A number of possible processes are considered as as a source for carbon injected into the atmosphere, however, non of these processes is able to fully cover all aspects (Higgins und Schrag, 2006). The largest, possibly mobile carbon reservoir is represented by free gas and especially gas hydrates in the upper sediment layers. Stability of gas hydrates depends on continuously high pressure and low temperatures. Consequently, increasing bottom water temperatures may start a chain reaction in which the greenhouse gas methane is released by dissociating gas hydrates and reaches the atmosphere where it will lead to further warming (positive feedback). This may possibly be further accelerated by submarine slides which would cause an even faster removal of gas hydrates from their stability zone, and subsequent dissociation. This process has been described as "Clathrate Gun Hypothesis" (Kennett et al., 2000).

If the PETM had been caused in this way, the release of ca. 2000 Gt carbon from gas hydrates should result in significantly more negative anomalies in carbon isotopes ($\delta^{13}C$) than have been detected. This is because the majority of carbon present in gas hydrates is the result of microbial turnover of organic matter (Archer et al., 2009; Milkov, 2004), which produces methane of very negative $\delta^{13}C$ ratios (<55) (Bernard et al., 1978; Whiticar, 1999). As such negative ratios are not observed, other hypotheses to explain the PETM have been discussed for some time. Some of these working hypotheses are rather unlikely. Among them

are enormous landslides which cause large masses of organic material to suddenly encounter ocean water rich in oxygen, the sudden drying-up of large marginal seas, as well as large-scale burning of peat areas. So far, non of these hypotheses could be supported by a solid data base (McInerney and Wing, 2011). A much more realistic hypothesis has been formulated by Svensen et a. (2004) based on the mapping of c. 700 ancient hydrothermal systems on the Norwegian continental margin (Møre and Vøring Basins). Their results are mainly from 2D seismic data. An extrapolation or interpolation to 3D showed that along the Norwegian continental margin alone about 3000 of these hydrothermal systems must have been active. The hydrothermal systems are always located above magmatic sill intrusions and appear to originate at the sill's upper end. It is understood that the systems are the result of magmatic intrusions into surrounding sediments, causing them to heat up and release carbon which is then able, together with pore waters released by metamorphosis, to migrate up to the sediment surface. This process is well understood from field studies in the Karoo Volcanic Province in South Africa (Svensen et al., 2003). The majority of hydrothermal systems in the Møre and Vøring basins ascends up to an Early-Eocene reflector that seems to coincide stratigraphically with the PETM. Hydrothermal systems exhibit three different morphologies at this reflector (Planke et al., 2005), ranging from pockmarks to mounds which may be interpreted as mud volcanoes. About 30 of the 700 hydrothermal systems terminate deeper than the Early Eocene reflector and may therefore be older. Two known zones of fluid escape reach the present-day seafloor (Gay et al., submitted), suggesting a later reactivation or even ongoing activity. Svensen et al. (2004) estimated the potential carbon release from these hydrothermal systems, which showed that under certain circumstances even more than 2400 Gt of carbon could have been produced. These calculations are based on several factors, some of which are well supported, e.g. the total organic carbon (TOC) content of the surrounding sediments, and amount and thickness of magmatic sills, while other factors are barely understood. Among those are the extent of sills in the North Atlantic Volcanic Province and the effectivity of hydrothermalism in terms of transport of carbon to the sediment surface.

Another unknown factor is the time component: how long does it take to transport carbon produced during contact metamorphosis up to the surface, and what is the time span over which igneous sill rocks form? Only a rapid carbon injection could have lead to the observed warming.

Therefore, to understand the likelihood of intrusive magmatism as an explanation for the PETM, it is necessary to closer investigate those factors, which requires measurements at active magmatic systems in sediment basins. This is possible in the Guaymas Basin in the Gulf of California (Fig. 1). The Guaymas Basin is an about 100 km wide area of the Gulf of California which has formed by rifting that started 12-15 Mio. years ago between the Lower Californian Peninsula (Baja California) and the Mexican mainland (Stock and Lee, 1994). The basin comprises two rift segments separated by a transform fault. Opening of the basin to form an ocean basin is thought to have occurred about 6 Mio. years ago (Lizarralde et al., 2007). Multichannel seismic lines (Fig. 2) acquired in 2002 on FS Maurice Ewing show magmatic sills, which intruded for

about 50 km to the northwest and for 40 km to the southeast of the rift axis (Lizarralde et al., 2010). Whereas the northwestern intrusions are marked by a strong, inconsistent reflector in biogenic sediments, the southeastern intrusions are characterised are cusped and have intruded into a mixture of biogenic and terrigenous sediments. Association of these reflectors with intrusions is suggested from drilling results of DSDP sites 481 and 477 in which igneous sill rocks were encountered. It is further confirmed by typical syn-magmatic deformation structures and indications for hydrothermal activity that are often observed in conjunction with magmatic intrusions (Hansen et al., 2005; Svensen et al., 2004). Below the intrusion-associated reflectors further sedimentary reflectors can be observed (Lizarralde et al., 2010), however, their amplitudes are much lower due to the high impedance contrast and 3-dimensional scattering of the rough sill surfaces, making them more difficult to observe. From the thickness of sediments overlying the sills and known local sedimentation rates, the maximum age of the intrusions may be inferred. Published sedimentation rates in the Guaymas Basin are about 1 km/Mio. years (Schrader, 1982). With a sediment thickness of 200-400 m, this gives a maximum age of about 400,000 years, but the intrusions are probably much younger.

Magma intruding into sediments with a high organic carbon content alters the sediments and promotes release of carbon as methane and carbon dioxide (Seewald et al., 1990; Svensen et al., 2003). These alteration processes have also been studied in the Guaymas Basin (Lonsdale and Becker, 1985; Simoneit and Lonsdale, 1982; Thornton and Seyfried Jr., 1987). The DSDP drill cores of Leg 64 showed that around the sills pore water was squeezed out, porosity decreased and calcareous and silicious microfossils were not present as they had apparently been dissolved (Galimov and Simoneit, 1982). Isotope-geochemical results of Chan et al. (1994) for sediments and hydrothermal fluids of DSDP Leg 64 (site 477) also show that the high temperatures generally cause dissolution of lithium (and probably other volatile elements) from sediments. However, there are no significant accumulations of lithium in the “vent fluids” and also no isotope fractionation compared to ridge basalts. This led Chan et al. (1994) to formulate the hypothesis that the Guaymas Basin is an open hydrothermal system with a constant supply of seawater as it is known from spreading axes not covered by sediments. Possibly the most interesting geochemical observation at the Guaymas fluid escape zones was the discovery of petroleum (Simoneit and Lonsdale, 1982) which directly showed the occurrence of thermal cracking of organic sediment contents. As long-chained petroleum components only constitute a small part of hydrocarbons produced during petroleum genesis, it is possible to infer that also large amounts of methane and maybe even carbon dioxide must have been produced in the course of magmatic intrusions. During a seafloor survey in 2009 a number of fluid escape sites were found, located above still warm magmatic intrusions (Lizarralde et al. 2010). Temperature measurements showed an increase in bottom water temperatures of 0.005 to 0.05 °C which is not explained by oceanography. Also, methane concentrations measured at 100 m above the seafloor significantly exceed background values (1.2 to 2500 nMol/kg). Photos from the seafloor show benthic ecosystems that are typical for cold seeps (Vesicomyide mussels, Vestimentifera tube worms, bacterial mats and crusts of authigenic carbonate).

1.5. Collaboration

The project was conducted in close collaboration with Prof. Carlos Morteira-Gutierrez of the National University of Mexico (UNAM) in Mexico City who joined the cruise with two engineers and four students and the company Volcanic Basin Petroleum Research AS in Oslo who sent two seismic processing specialists. Furthermore, we received support Dr. Dan Lizarralde at Woods Hole Oceanographic Institution (WHOI) who have been working in the study area before.

2. Detailed report

2.1. Use of resources and achievements compared to the envisaged goals

The resources were largely used as described in the project proposal except that the transport costs for the flights to Mexico were much higher than anticipated which meant that the bulk of the consumable costs of the project (all except ~ 7000 EUR) had to be covered by departmental funds at GEOMAR.

2.2. Main expenditures

The main expenditures included the container transport to Manzanillo, Mexiko and from Guadalquivir, Equador as well as the flights. The second main item of expenditure was personnel. We hired Dr. Sudipta Sarkar for the geophysics postdoctoral research assistant position and Dr. Sonja Geilert for geology doctoral candidate position pro rata.

2.3. Necessity and suitability of the conducted work

As expected all work that we conducted was necessary to achieve the objectives of the project and the work was found suitable to study the scientific questions. Because of technical problems (overheating of data modems) we could not collect any high-resolution 3D seismic data, which has limited the quantification of the volcanic intrusions. It turned out that this instrument failure was fortuitous nevertheless because it required us to collect more 2D seismic lines, which resulted in the discovery of the black smoker, which was very important for the project.

2.4. Envisaged uptake

The results of the project as published in Berndt et al., Geology, 2016 have changed the way how the community looks at intrusion-related fluid escape from the sea floor. The results form the basis of a follow-up project to return to the study area with an ROV, an AUV, and the upgraded 3D seismic equipment (Sonne Project MAKSIM, approved) and to drill the area with the JOIDES Resolution (Drilling expedition 385 approved and scheduled for September 2019).

2.5. Developments in the field in the duration of the project

During the project two other cruises have visited the study area using the ship PUMA in 2015 and Nautilus in 2017. Both cruises were primarily concerned with marine biology and did not address the research questions of MAKS.

2.6. Publications and publications in preparation

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In prep.:

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3. Appendices

3.1. Success control report

a. Contribution to the political goals of BMBF

The project MAKS has led to a better understanding of the Earth system which is one of the key goals in FONA. In particular we have delivered constraints for climate modelling by testing of the hypothesis that submarine carbon seepage from magmatic system may lead to global warming. By using these constraints for modelling the PETM the climate models will be improved in the future. This will result in more reliable climate forecasts. Also, the results of this modelling will make clear if hydrate dissociation is required to inject large amounts of carbon into the atmosphere quickly. Because hydrate dynamics are potentially dependent on human activity there is a clear need for understanding the involved risks.

b. Scientific/technical results

b1. Seismic imaging of sill intrusions and fluid sources

A large number of sill, i.e. magmatic intrusions, are visible in the reflection seismic data collected during SO252 (Fig. 1). During magma emplacement, hydrocarbons and pore fluids are liberated from the surrounding sediments due

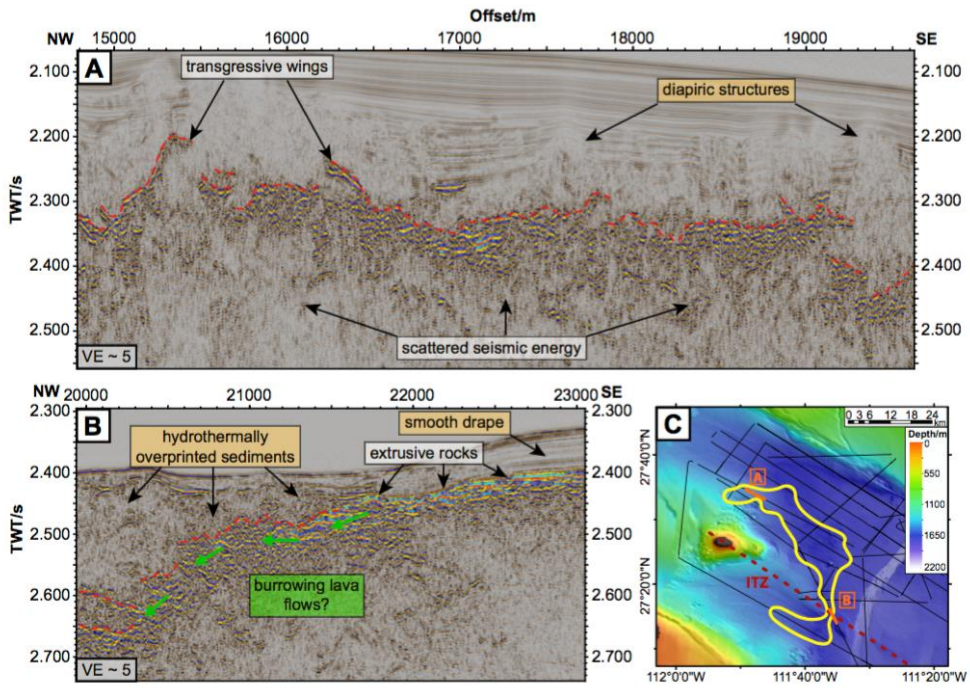

Fig. 1: Typical examples for intrusive (A) and extrusive (B) volcanic successions encountered in the Guaymas Basin. Distribution of extrusive rocks (C) (after Behrendt, 2016).

to contact metamorphic reactions and are thought to migrate to the seafloor in hydrothermal vent complexes. Hundreds of these vent structures have been detected at the Norwegian Margin, but the amount of carbon released through the vents is still controversially discussed. We have interpreted the sill morphology and types of fluid migration. Both are found to vary significantly throughout the basin and seem to depend mainly on the depth of sill emplacement. Sills intruded in the deeper parts of the sedimentary column usually display classical sheet- or saucer-like shapes and are mostly accompanied by pipe structures. On the other hand, intrusions emplaced in the upper 300m often feature complex morphologies suggesting strong interactions and mingling between magma and the weakly consolidated sediments. In some cases, the magma propagation seems to be flow-like due to extensive liquefaction of the host rock. In the shallow parts of the basin, fluid migration is dominated by extensive sediment remobilisation and distributed fluid flow.
The differences in fluid escape features can be explained by consolidation related changes in strength, pore water content and permeability which favour focused fluid flow in the deeper parts and sediment remobilisation in the very shallow parts. Furthermore, the results highlight the impact of the rheological behaviour of the host rock for the morphological evolution of the sills and show that sill emplacement is closely related to fluid migration in the shallow subsurface.

b2. Interaction between intrusions and gas hydrates

Marine methane hydrates naturally occur down to a few hundred meters below the sea floor, where appropriate high-pressure and low-temperature conditions

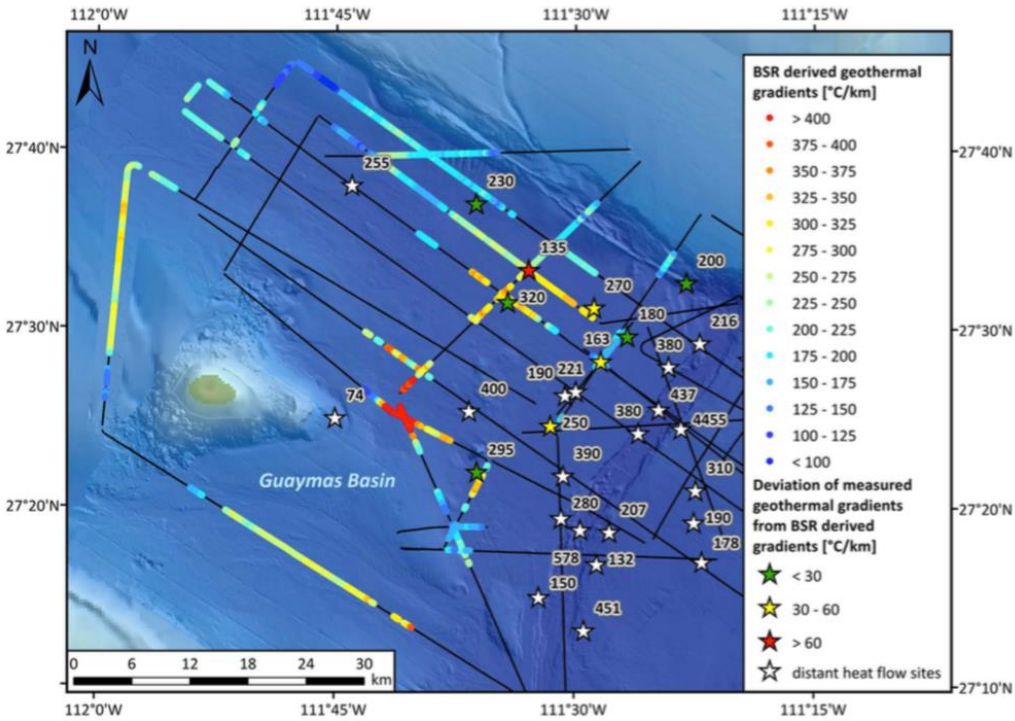

Fig. 2: Comparison of gas hydrate BSR-derived geothermal gradients and heatflow lance derived geothermal gradients illustrating the high temperatures in the sediments due to the volcanic intrusions (after Moser, 2016).

and a sufficient supply of gas and water ensure their generation and stability. Geophysical data collected during SO252 in the Guaymas Basin, Gulf of California, show a clear and widespread but unusually shallow bottom simulating reflector (BSR) in connection with recent rift-related igneous intrusions into organic rich marine sediments. Using a large number of high-resolution multichannel seismic data, we identified the BSR and determined the thermal state of the Guaymas Basin. The sub-bottom BSR depth ranges between 22 and 138 m, which indicates a high thermal variability (91-605 C/km) within the basin and matches well with available field-based measurements. The most likely processes that may control this variability are the intrusion of magmatic sills and small-scale convection of pore fluids possibly related to the sill intrusions. A comparison of BSR derived geothermal gradients with the subbottom depths of the sill intrusions shows a general trend of a decreasing geothermal gradient with an increasing subbottom sill depth (Fig. 2). However, there are several deviations, such as a concave alignment of the top of the sills probably causing a boiler effect and, therefore, extremely high geothermal gradients. The presented results show the dependence of the observed thermal variability on the recently intruding sills. Furthermore, the BSR is not identified in the areas affected by submarine landslides, indicating the absence of a sufficient amount of gas in the shallow sediments limits gas hydrate formation, probably, due to poor permeability of the slide materials. The results suggest a prevalence of temperature sensitive shallow gas and gas hydrates. If new large-scale intrusions take place, this may provide an efficient mechanism to release light carbon via gas hydrate dissociation. The release of hydrate-bound light hydrocarbons could trigger a potential climate change like the Paleocene-Eocene Thermal Maximum, but currently, there is no substantial evidence for any gas hydrate destabilization in this part of the basin.

b3. Evidence for short lived venting from pore fluid geochemistry

The Guaymas Basin in the Gulf of California is an ideal site to test the hypothesis that magmatic intrusions into organic-rich sediments can cause the release of large amounts of thermogenic methane and CO2 that may lead to climate warming. In this study, pore fluids close (~500 m) to a hydrothermal vent field and at cold seeps up to 20 km away from the northern rift axis were studied to determine the influence of magmatic intrusions on pore fluid composition and gas migration. Pore fluids close to the hydrothermal vent area show predominantly seawater composition (red symbols in Fig. 3), indicating a shallow circulation system transporting seawater to the hydrothermal catchment area rather than being influenced by hydrothermal fluids themselves. Only in the deeper part of sediment core GC09, composed of hydrothermal vent debris, Sr isotopes indicate a mixture with hydrothermal fluids of ~3%. Also cold seep pore fluids show mainly seawater composition. Most of the methane is of microbial origin and consumed by anaerobic oxidation in shallow sediments, whereas ethane has a clear thermogenic signature. Fluid and gas flow might have been active during sill emplacement in the Guaymas Basin, but ceased 28 to 7 thousand years ago, based on sediment thickness above extinct conduits. Our results indicate that carbon release depends on the longevity of sill-induced, hydrothermal systems, which is a currently unconstrained factor.

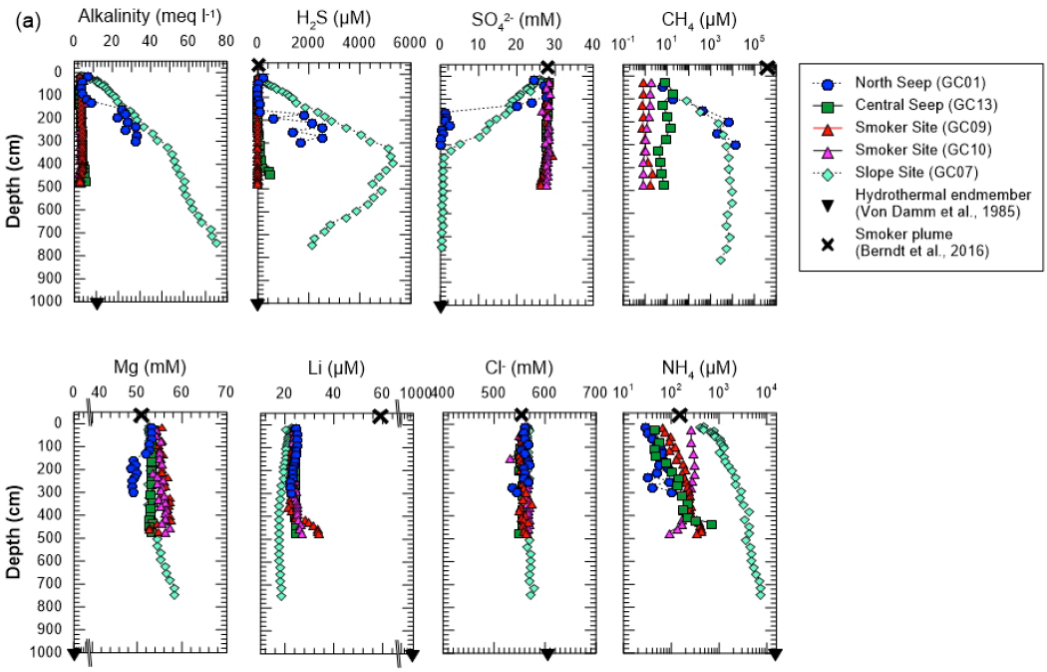

Fig. 3. Geochemical signature for different studied seep sites showing that the hydrothermal signature (found at the smoker site) has already disappeared although the sites cannot be older than a few thousand years (from Geilert et al., subm.).

b4. Carbon release due to sill intrusions

B3. Silicate diagenesis traced by Si isotopes

The Guaymas Basin is well suited to study silicate diagenesis as high sedimentation rates result in a thick siliceous sediment layer, composed mainly of diatoms. Silicon (Si) isotopes in pore fluids, diatoms, and clays from hot vents and cold seeps have been studied with the aim to investigate fluid sources and fluid-sediment interactions.

Dissolved silica concentrations (dSi) in pore fluids of short sediment cores (<30cm) increase with depth and range from 0.04 to 0.86 mM. Si isotope compositions (δ^{30}Si) vary between 0.5 and 2.1 ‰ (Fig. 4). Pore fluid dSi of long sediment cores (up to 5m) range from 0.37 to 1.3 mM and δ^{30}Si signatures span an extreme range from -0.3 to 2.5 ‰. The isotopic values are the highest and lowest observed so far in pore fluids. They reflect a mixing system of hydrothermal fluids and seawater (δ^{30}Si = 1.8 ± 0.3 ‰ (2σ)) and are further affected by dissolution and precipitation reactions in the sediment (Geilert et al., 2015; in prep.). Silica concentrations and Si isotopes in the Guaymas Basin are strongly influenced by the local temperature regime. Highest dSi and δ^{30}Si signatures are found close to the hydrothermal vent sites where early diagenetic processes are accelerated, including Si release from diatoms and incorporation of light Si isotopes into authigenic phases (Fig. 4). Close to the hydrothermal vent

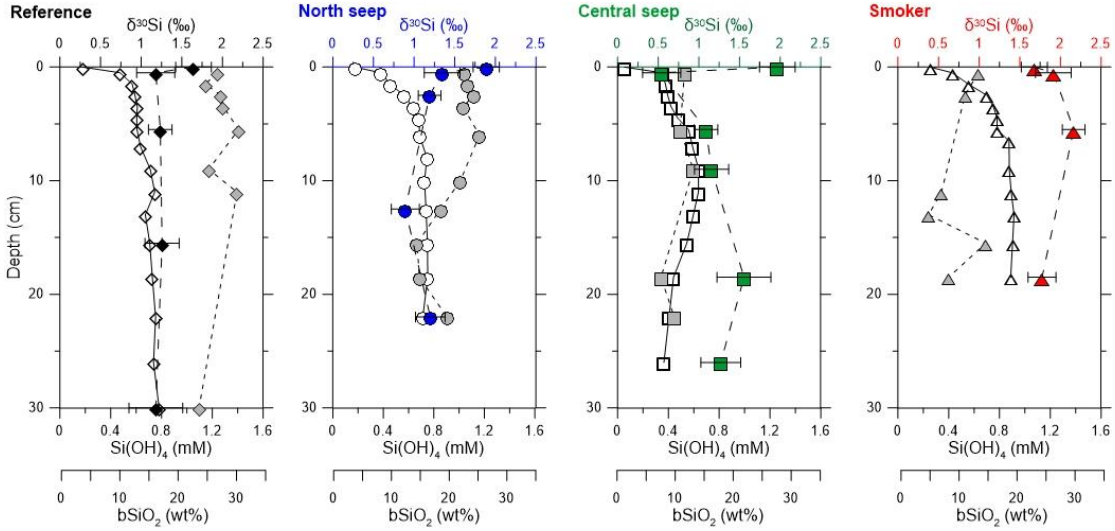

Fig. 4: Silica concentration (empty symbols), biogenic silica content (bSiO2; grey symbols), and Si isotopes (colored symbols) for sampling stations Reference, North seep, Central seep, and Smoker site.

field mixing with isotopically light hydrothermal fluids likely occurs. Ongoing analyses of diatom and clay $\delta^{30}Si$ will complete the data set. Our data demonstrate that Si isotopes can be used to characterize early diagenetic processes and to determine sources and sinks of the present and past silica cycle.

B4. Carbon release due to sill intrusions

During the opening of a new ocean magma intrudes into the surrounding sedimentary basins. Heat provided by the intrusions matures the host rock creating metamorphic aureoles potentially releasing large amounts of hydrocarbons. These hydrocarbons may migrate to the seafloor in hydrothermal vent complexes in sufficient volumes to trigger global warming, e.g. during the Paleocene Eocene Thermal Maximum (PETM). Mound structures at the top of buried hydrothermal vent complexes observed in seismic data off Norway were previously interpreted as mud volcanoes and the amount of released hydrocarbon was estimated based on this interpretation. Here, we present new geophysical and geochemical data from the Gulf of California suggesting that such mound structures could in fact be edifices constructed by the growth of black-smoker type chimneys rather than mud volcanoes. We have found evidence for two buried and one active hydrothermal vent system outside the rift axis (Fig. 5). The vent releases several hundred degrees hot fluids containing abundant methane, mid-ocean-ridge-basalt (MORB)-type helium, and precipitating solids up to 300 m high into the water column. Our observations challenge the idea that methane is emitted slowly from rift-related vents. The association of large amounts of methane with hydrothermal fluids that enter the water column at high pressure and temperature provides an efficient mechanism to transport hydrocarbons into the water column and atmosphere, lending

support to the hypothesis that rapid climate change such as during the PETM can be triggered by magmatic intrusions into organic-rich sedimentary basins.

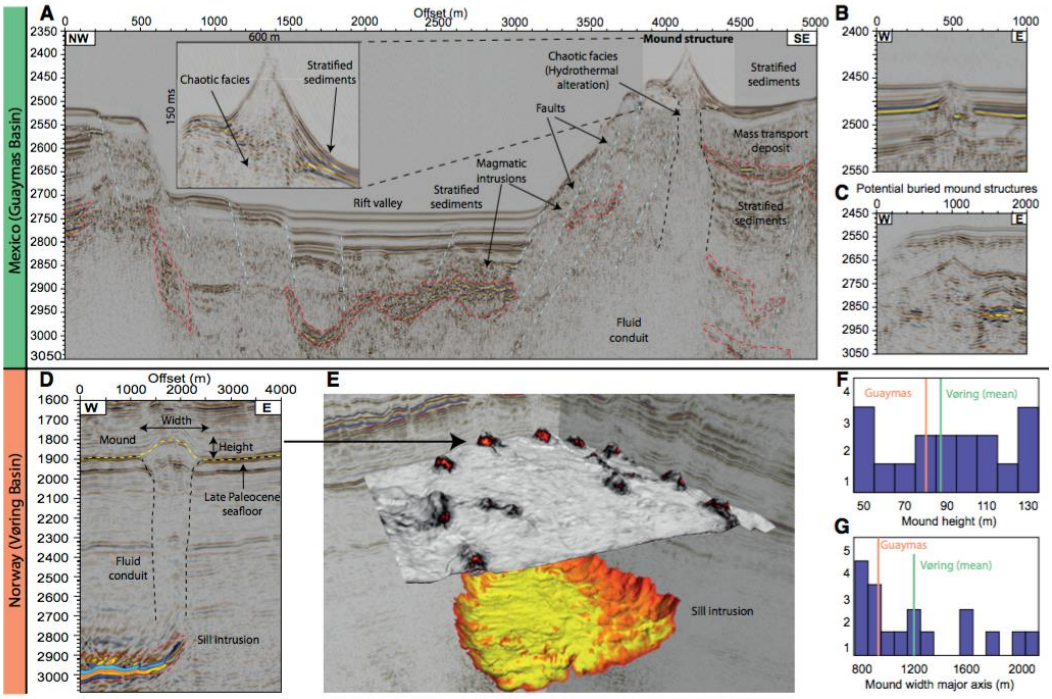

Fig. 5: Comparison of seismic signature of active black smoker (A) and extinct structure in Guaymas Basin (Gulf of California) (B,C) and extinct structures observed in Vøring Basin during opening of Northeast Atlantic off Norway (D,E). Width (F) and height (G) of active black smoker in Guaymas Basin are similar to those of structures in Vøring Basin, as indicated by red line in blue histograms. Green lines are average width and height. Vertical axis on all seismic images shows two-way traveltime (in ms) (from Berndt et al., 2016).

c. Future use of the results

The results presented in this thesis have been taken up by the scientific community and have already spawned two major campaigns: the follow-up project MAKSIM in which we will investigate the newly discovered black smoker, and IODP Leg 385 during which we will drill into the vent structures to groundtruth the geophysical findings.

A Marie-Curie project was submitted in which Esther Velasco (University of Madrid) is planning to study microorganisms in extreme environments. Hydrothermal sediments sampled close to the Smoker Site are planned to be studied in her proposal and GEOMAR is a collaborator in this project.

An interesting unexpected uptake of the research is a host of micro-biological studies that were triggered by our research. These are mainly being conducted at ETH Zürich (Mark Lever) and at the University of North Carolina Chapel Hill

(Andreas Teske). A host of new micro-organisms is associated with the hydrothermal systems and provides insights into the deep biosphere.

d. Work that did not result in solutions

All work conducted during the cruise has led to scientific results and has been or will be published (see section 2.6)

e. Dissemination for potential users

The data has been presented at major international conferences (American Geophysical Union Annual Meeting, Goldschmidt Conference) and in the peer-reviewed literature. As such it is available to the stake holders.

f. Compliance with time and budget plans

There were no deviations from the time and budget plans.

3.2. Document control sheet

(next page)